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PROPERTIES OF NATURAL RAINFALLS AND THEIR SIMULATION IN THE LABORATORY FOR PESTICIDE RESEARCH

R C Simmons

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Agricultural Research Council Weed Research Organization, Begbroke Hill, Yarnton, Oxford, OX5 1PF

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INTRODUCTION

Field studies involving rainfall are difficult because of the unpredictability and variability of natural rainfall. We therefore decided to build a rainfall simulator. This report sets out some of the criteria used to arrive at the chosen specification and examines some of the methods available to fulfil those criteria. It will become evident that the unit selected is a compromise between research requirements and physical limitations, and other workers may well choose some other compromise if their aims or working conditions are different from our own.

OBJECTIVES

The presence or arrival of precipitation can affect the performance of both foliar and soil-applied herbicides. The main direct and indirect effects of rain on foliar applied herbicides are:

1. Impact can cause removal or redistribution of herbicide on a leaf.

2. Runoff of water can cause removal or redistribution of herbicide.

3. Impact can cause deformation of the plant, altering the target area and angle for subsequent spraying.

4. Rain can alter the leaf surface by removing dust or damaging the cuticle.

5. The presence of water on the leaf will alter the microclimate of the leaf, raising the humidity and perhaps lowering the surface temperature.

6. The presence of water on the leaf may provoke physiological changes in the plant.

Some of these effects are dependent on the energy with which individual drops strike the leaf, and this in turn will depend on the size, number and velocity of the drops. Most will be influenced by the intensity and duration of the rain. Similarly the effects on herbicides within or upon the soil will include:

1. physical deformation and disturbance of soil near the surface,

2. lateral redistribution, or removal,

3. solution of solid particles,

4. redistribution by leaching in solution,

5. physical movement of solid herbicide or herbicide on soil particles

downward through channels in soil.

Again, as well as the total quantity of rain applied, intensity and impact energy will be important so a simulator design must be able to reproduce these factors correctly.

PROPERTIES OF NATURAL RAINFALLS

The properties of rain which the simulator must reproduce are: duration of rainfall, intensity, drop size(s) and drop impact energy. The drop size and energy of real rainfalls vary with intensity: there are no precise relationships, but a number of workers have shown general correlations between intensity and drop size distributions which can be used to define suitable drop size spectra for a rain simulator. To give values to these properties, we must examine the qualities of real rainfall.

Intensity

Most natural rain showers in Great Britain have intensities between 1 and 5 mm/hour. (Met. Office unpublished information and meteorological records at WRO). The simulator should therefore be able to produce rain intensities below 1 mm/hour. Intensities greater than 5 mm/hour are much less common (44 out of 7000 showers analysed by the Met. Office at Boscombe Down); however it is relatively easy to achieve high intensities with a simulator so an extended range can be included in the specification without penalty.

Drop size distribution

Various authors (Laws & Parson, 1943; Marshall and Palmer, 1948; Best, 1950) have made estimates of the relationship between the size distribution of raindrops and the intensity of the rain. The most recent paper (Mason and Andrews, 1960) confirms the basic relationships found by earlier work, but was able to define different drop size characteristics for different types of rain identifiable by their radar echoes. For our purposes, there is sufficiently little difference between most types of rain (with the exceptions of thunderstorms, and of intense storms where coalescence of drops occurs) for us to take an average measure of the drop size distribution in continuous frontal rain as our standard. Table 1 shows the relationship between median drop diameter and intensity, as defined by the equation attributed to Marshall and Palmer, and quoted in Mason and Andrews:

$D = 0.92I^{0.21}$ where D = median diameter and I = intensity.

Table 1.

Rainfall intensity mm/hour	Median drop diameter mm
0.1	0.60
0.5	0.85
1.0	0.98
2.0	1.14
3.0	1.24
4.0	1.31
5.0	1.38
10.0	1.59

The median drop size is the drop size such that half the total volume is contained in drops smaller than the median. This is not the same as the modal drop size - the most frequently occurring drop sizes are naturally smaller than the median volume drop size since more small drops are needed for a given volume.

Table 2 (Best, 1950) shows the volume of each size of drop present in natural rains at intensities of 0.5, 1 and 5 mm/hr.

Best's figures are broadly in agreement with those of other workers, though Mason and Andrews (1960) consider that most quoted relations between drop size and intensity overestimate the numbers of small drops.

Table 2. Volume of water present as drops of each size in a volume of $1 m^3$ of air.

Intensity		mm/hour	
	0.5	1.0	5.0
Drop diameter	volume of water mm^3/m^3		
0.00 - 0.25	1.3	1.6	2.7
0.25 - 0.50	4.4	5.7	10.1
0.50 - 0.75	6.9	9.5	17.9
0.75 - 1.00	7.7	11.6	24.8
1.00 - 1.25	6.8	11.7	29.7
1.25 - 1.50	4.8	10.0	31.9
1.50 - 1.75	2.9	7.3	31.5
1.75 - 2.00	1.4	4.7	28.7
2.00 - 2.25	0.6	2.6	24.5
2.25 - 2.50	0.2	1.3	19.4
2.50 - 2.75	0.1	0.6	14.4
2.75 - 3.00		0.2	10.1
3.00 - 3.25		0.1	6.6
3.25 - 3.50			4.0
3.50 - 3.75			2.4
3.75 - 4.00			1.3
4.00 - 4.25			0.6
4.25 - 4.50			0.3
4.50 - 4.75			0.1
4.75 - 5.00			0.1

The volume is related to the drop diameter by the relation $V = {}^4/_3 (0.5D)^3$, hence we can find the volumes of each class of drop in the table. Since we know the total volume of water present in each class of drop size, per m^3, we can divide one by the other and find the number of drops present in each individual sample. Hence we can make an equivalent table to the one above, but for number of drops.

Table 3.

Drop dia. mm	No. of drops in $1m^3$ 0.5 mm/hr	1.0 mm/hr	5.0 mm/hr
0.0 - 0.25	1250	1585	2685
0.25 - 0.50	160	208	364
0.50 - 0.75	54	74	140
0.75 - 1.00	22	33	71
1.00 - 1.25	9	16	40
1.25 - 1.50	3.5	7	23
1.50 - 1.75	1.3	3.3	14
1.75 - 2.00	0.4	1.3	8
2.00 - 2.25	0.1	0.5	4.9
2.25 - 2.50	0.03	0.2	2.8
2.50 - 2.75	0.01	0.06	1.5
2.75 - 3.00		0.02	0.8
3.00 - 3.25			0.4
3.25 - 3.50			0.2
3.50 - 3.75			0.1
3.75 - 4.00			0.04
4.00 - 4.25			0.02
4.25 - 4.50			0.01
4.50 - 4.75			0.01
4.75 - 5.00			0.01

Using the values in the table above and the values of terminal velocities quoted by Smith and Wichsmeier (1962), one can calculate the number of drops of each size class arriving on a given area of horizontal surface per unit time thus:

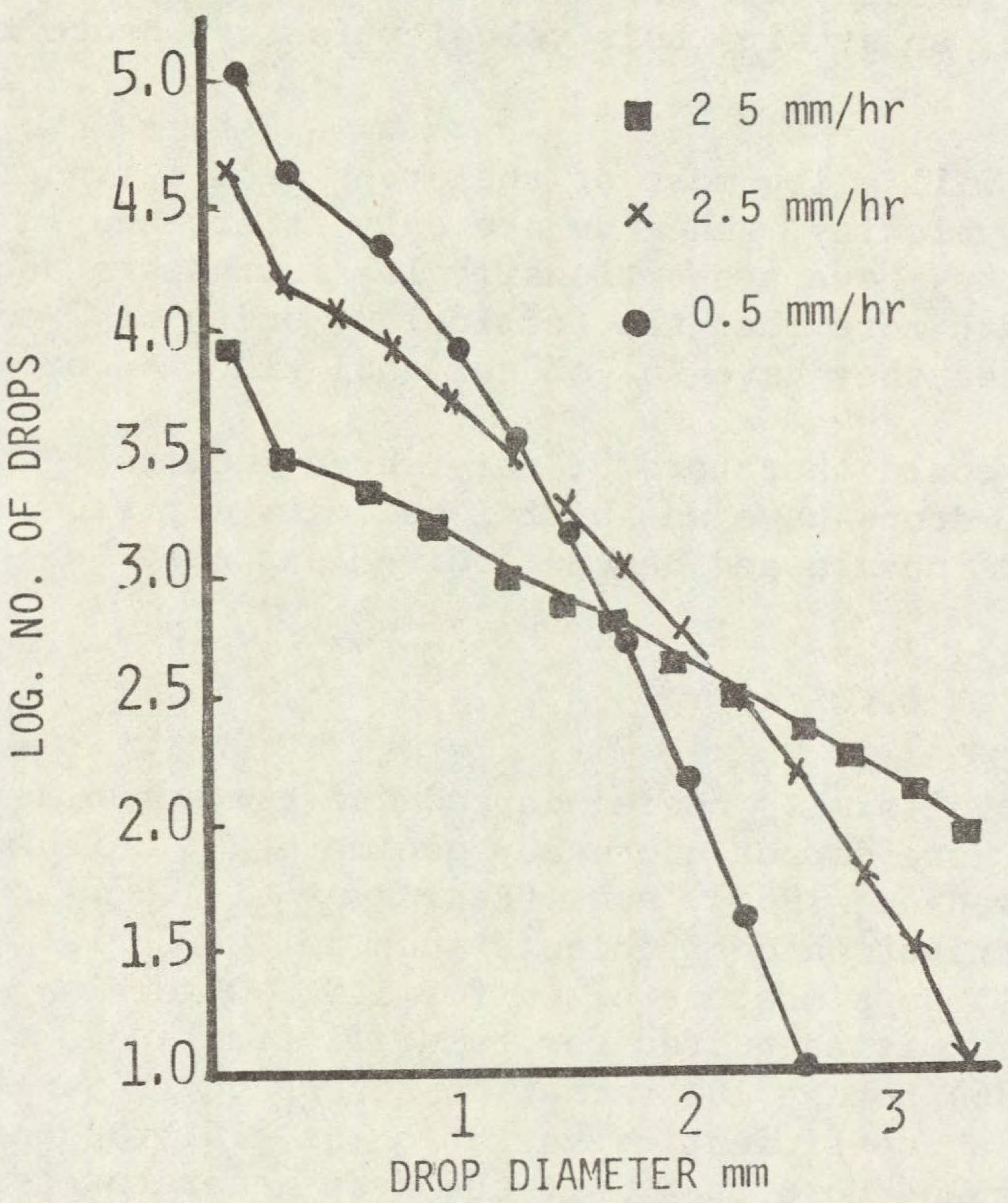
$$\text{Drops } m^{-2}s^{-1} = \text{drops } m^{-3} \times \text{Terminal velocity } (ms^{-1})$$

Graph 1 shows this quantity plotted against drop size class for three specimen intensities. (In order to allow comparison the drop numbers have been adjusted for intensity, i.e. expressed per mm hr^{-1}).

Most of the drops for a realistic simulator will therefore have a diameter of less than 0.25 mm. However, failure to represent the larger drops will result in errors in the kinetic energy of the rain.

Even at 5 mm/hour, though, less than 2% of the rain is represented by drops greater than 3 mm dia, so omission of drop forming elements for these sizes will not result in serious error.

GRAPH 1 DROP SIZE DISTRIBUTIONS IN REAL RAINS



There are no known devices which will accurately reproduce the drop spectra discussed above; however selection of the correct drop forming elements can produce a spectrum sufficiently close to real rain for many purposes, at a particular intensity. Changing intensity may demand a change in the drop forming devices.

Terminal velocity

Ideally all the drops should reach the target travelling at their terminal velocity. Table 4, reproduced from Smith and Wichsmeier (1962) shows the terminal velocity of raindrops falling in free air, and the distances necessary to attain 95% of that velocity for a droplet starting at rest.

Table 4.

Drop diameter (mm)	Terminal velocity (m/sec)	Free fall to attain 95% T.V. (m)
0.25	1.0	
0.5	2.0	
1.0	4.0	2.2
2.0	6.5	5.0
3.0	8.1	7.2
4.0	8.8	7.8
5.0	9.1	7.6
6.0	9.3	7.2

From the table it is apparent that a free fall of 8 m (25 feet) is required to ensure terminal velocity for all drop sizes (large drops have proportionally less air resistance, so attain their velocity faster, hence the peak at 4 mm).

A fall of 5 m will allow most of the drops from our notional simulator to assume terminal velocity, since we are only interested in forming drops 3 mm, and because they have proportionally less air resistance, we may assume that 3 mm drops reach more than the terminal velocity of 2 mm drops, say 7 m/sec, at which speed they have 76% of terminal kinetic energy.

A fall of 5 m could therefore be considered acceptable. (In the case of nozzle networks, drops have an initial velocity imparted by the pressure of ejection from the nozzle and hence require less free height to ensure terminal velocities).

Uniformity

The degree of uniformity needed depends on the experimental precision required. Some workers do not quote any estimates of uniformity (Bubenzer and Meyer, 1965; Swanson, 1965), some (Rawitz et al, 1972) have used one of the irrigation distribution coefficients such as the Christiansen coefficient (Christiansen, 1941) as a measure of uniformity. Others have quoted a coefficient of variation. Uniformities quoted for rainfall simulators vary widely. Munn and Huntingdon (1976) note a 16% variation across their target area. Romkens et al (1975) claim a coefficient of variation of 8.5% for their moving drop generator simulator and note that, if the drop generator is static, the variation rises to 31%.

Water quality

Rain generally contains low levels of suspended solids and dissolved salts owing to the limited opportunities for a raindrop to absorb such materials. However, gases present in the atmosphere (predominantly CO_2 and SO_2) will dissolve in the rain to make it weakly acidic. Mains water in many areas will therefore require some form of treatment such as deionising, to make it suitable. Some economy in treatment costs may be possible by collecting rainwater from building roofs and using this in preference to mains water, though it was not found to be economic to do so at WRO.

Wind effects

Real rainfalls often have a lateral component of velocity due to wind. There are two consequences which may be important. The impact angle is altered, and may cause differences in the way drops splash, and the direction of movement of dislodged material. The surface structure of the ground, and of objects upon it, will cause local variations in wind speed and direction, which themselves will cause uneven deposition of rain.

It is difficult to simulate the effect of wind in an indoor rain simulator; the requirement for a uniform airflow over the whole target area calls for the simulator to be located in the working section of a wind tunnel with a suitable velocity gradient to target level. When a laminar flow over the target area has been produced, the experimenter can introduce whatever disturbing elements he wishes to model.

A REVIEW OF DESIGNS FOR RAIN SIMULATION

Few if any rain simulators were designed with pesticide research in mind. Some experimenters (Doran and Anderson, 1975) consider a watering can sufficient for simulating rain effects on a soil applied herbicide, other workers have devised more complicated devices (Brockman, Duke, Hunt, 1975) or have adapted commercial irrigation equipment (Jablonska-Ceglarek et al, 1976) but again intended primarily for the less rigorous demands of soil applied herbicides, though some (Upchurch, Coble and Keaton, 1969) have used these techniques on foliar herbicides. Most of the work on devising simulators which have a drop size distribution and kinetic energy similar to natural rainfall has been done by hydrologists or soil scientists. Development of simulators has followed two distinct paths, clearly distinguished by the type of drop forming element used. One type uses nozzles to produce drops, while the other relies on tubes, yarns or holes to produce a series of drips.

Nozzle types

Development of nozzle type simulators goes back to before the second World War, and early work in the US soil conservation service produced a series of nozzle simulators for use in research on soil erosion. The Rainulator (Meyer and McCune, 1958; Hermsmeier et al 1963) is an example of a downward spraying nozzle device using standard 'Spraying Systems' 80100 nozzles. Swanson (1965) describes a device using similar nozzles, but having a rotating boom assembly to allow application over a large plot more evenly, the nozzles being unevenly spaced to compensate for the speed difference between the inner and outer ends of the boom.

Bertrand and Parr (1961) describe a portable nozzle simulator constructed at Purdue University, for use on small plots, which was later modified by Amerman et al (1970) and Rawitz et al (1972) by the addition of a rotating sector shutter to intercept some of the nozzle output and hence achieve a more realistic delivery rate. This technique had also been used by Morin et al (1967) on a similar device, and, more recently, by Grierson and Oades (1977). A simulator described by Nassif and Wilson (1975) and subsequently modified (Jacob, 1978) to permit easier adjustment, has horizontal slats to intercept a portion of the nozzle output and thus permit operation at lower intensities of rainfall. Bubenzer and Meyer (1965) attempted to combine the reduction of effective application rate with improved uniformity by rapidly oscillating a nozzle across the surface of a plot. Where extreme portability was required, some equipment has been made with a hand operated boom (Costin and Gilmour, 1970) and the intensity and evenness then depend upon the skill of the user. Sloneker and Moldenhauer (1974) have shown that for some effects upon soil, intermittent application such as happens when a boom is moved across a plot, or oscillated slowly, does not produce the same effects as continuous application. Turner (1965) accepts the difficulty of obtaining a good drop spectrum at realistic application rates but considers that, provided the characteristics of the simulated rain are known, this need not be a disadvantage, and decided upon a static nozzle network only 32" above the target for his work on surface flow over soils, and used Spraying Systems ¼" HW or 8002E nozzles spaced so as to achieve maximum uniformity.

Other types

Workers whose needs could not be met by nozzle type applications, or who considered the mechanical simplicity of the static drip device an advantage, have constructed a variety of simulators using yarn, tubes or holes as the drop forming elements. Ellison and Pomerene (1944) constructed a rainfall applicator consisting of a supply tank, with perforated bottom, below which was suspended a screen of cheesecloth supported on chicken wire. The cloth sags through the depressions in the wire and short lengths of wool yarn hang from each depression. The drops are formed at the ends of the yarn. The screen is oscillated to improve the evenness of distribution. Static drip devices usually require more attention to distribution, because unless deflected by air currents drops tend to fall almost vertically, falling in a well defined area. Mütchler (1965) found a normal distribution for the impact position for drops falling in a shielded tube, and devised a formula for calculating uniformity from drop size and drop tube spacings. Later workers have tried to improve the uniformity of application by oscillating the drop-forming assembly (Steinhard and Hillel, 1966) or by a combination of oscillation and rotation (Römkens et al, 1975). Hart (1960) describes techniques for calculating the uniformity of nozzle networks, and Hall (1969) shows how computer simulations can be used to design and predict the performance of nozzles in networks. Page (1976) found it more convenient to oscillate the target in a pseudo-random manner using motors and specially cut cams. Simulators designed for use in the field normally do not have such elaborate provisions for randomisation, because air currents tend to increase the uncertainty of drop trajectories, and field plots do not usually require such precise treatment as laboratory units. An example of a field unit using yarn is described by Melvin and Bisal (1964) and an interesting design using polythene catheter tubes by Munn and Huntingdon (1976). As well as yarn and simple tube drop formers, some workers have devised other ways of forming drops, some simple, some more complex. British Patent 1,131,095 describes a method of producing uniform drops through a precisely drilled PTFE plate. A replaceable pad of filter paper controls the flow and retains solid particles which might block the orifices. The equipment is intended for the testing of waterproof fabrics, but might find application in other fields because of the relative ease of manufacture. A much more complex drop forming device is described by Mütchler and Moldenhauer (1963) consisting of a series of different sized tubes assembled telescope fashion; the largest tube controls the drop size, the smallest, the flow.

Page (1976) considered the effort needed to make these drop formers too great, and devised a simple drop tube assembly under which a frame containing larger tubes could be clamped. In this way the drop size could be varied while retaining the smaller tubes to control the flow. Römkens et al (1975) used hypodermic syringes to form the drops, and controlled the flow rate by causing a motor driven plate to depress the plungers of the syringes. This system gives very accurate control of intensity but limits the amount of rain applied, in this case to about 3 mm.

It is evident from the existing literature that the design of rain simulators chosen by experimenters depends on the particular features of the simulation considered important. Superimposed on this are considerations of cost, portability and ease of use. In some cases pesticide scientists have chosen a deliberately unrealistic wetting treatment for plants or parts of plants (Phillips, 1969; Caseley et al, 1976) on the grounds that such treatments were easier to reproduce and therefore constituted a useful standard for comparison of pesticide formulations, or were sure to exert the maximum effect of mechanical removal, and hence were a useful research tool. Such requirements are probably best handled by empirical methods rather than by trying to extend the range and scope of a rain simulator.

METHODS OF DROP FORMATION

Static drip tubes

Drip tube type devices inherently produce single size drops. The drop size spectrum of natural rain can therefore only be approximated by combining different sizes of drip tubes. Each size present must be capable of giving coverage of the target area, so a large number of tubes must be used to maintain uniformity. Large differences in tube diameter produce only small differences in drop size, for example Page (1976) states that 0.8 mm O.D. tubes produce 3 mm drops, while 5 mm tubes produce 5 mm drops. To produce drops 1.5 mm from tubes is difficult owing to the ease with which such small tubes block up, the difficulty of detaching the drops and the high head pressures needed to produce a reasonable flow. Hence static drip simulation of rains of the low intensities we are considering will not correctly represent the size distributions shown in Graph 1. In soil erosion and leaching studies, such considerations are less important, since the smaller classes of drop represent only a small volume and make a very small contribution to total kinetic energy, so the practice of representing them by a smaller number of larger drops is acceptable. For many kinds of research, however, small drops which wet the leaves without causing significant mechanical disturbance may be an important factor, since preliminary experiments with various nozzle types suggested that the smallest sizes of droplets are important in the initial wetting of the leaves.

Rotary disc atomisers

In the rotary disc atomiser, liquid is introduced on to the surface of a rotating disc. Inertial forces cause it to be broken into drops as it is thrown off the disc edge.

Rotary atomisers have been adapted for low volume pesticide application (Taylor, Merritt and Drinkwater, 1976) and the ability to deliver low volumes with an accurately controlled drop size suggests the possibility of using them for rain simulation.

The production of large drops from discs requires low speeds and limited flow rates, and smaller satellite drops are also produced, though this need not be a disadvantage for rain simulation provided it is consistent. The inherent spray deposition pattern for a rotary disc is a well-defined circle, (typically 1-2 m radius). The size of the circle is defined by the drop size and tangential velocity and therefore varies with disc speed.

To generate an approximation to real rainfalls, one would need 3 or 4 sets of discs, each set revolving at a different speed to generate a different drop size, and each set independently fed from a separate flow controller. Each set would have to be capable of covering the target with an even distribution of its particular drop size. Mounting all the discs so that none interfered with the output of the others while maintaining satisfactory uniformity over a useful target area, might pose a difficult problem which would outweigh the potential advantages of rotary atomisers.

Nozzles

Various types of nozzle have been used for rain simulation in the past. Simulators having travelling booms need nozzles with a flat fan-shaped spray pattern which can be overlapped to give an even swath. In order to achieve the right drop size distribution, the nozzle has to have a much larger output than a conventional herbicide sprayer, and the Spraying Systems 80100 has been a popular choice (Meyer, 1958; Swanson, 1965). Where drop size distribution was not considered a prime factor, for instance in soil leaching studies, some workers (Beckman et al, 1975) have used conventional pesticide application nozzles.

For simulators whose nozzles are arranged in a static array, nozzles with a circular or rectangular spray pattern are required. To obtain a solid cone of spray with the appropriate drop size distributions, a swirl type nozzle is the most suitable. This type of nozzle has angled vanes within the body of the nozzle which imparts a circular motion to the water. The pressure needed for atomisation is relatively low and, by increasing the size of the nozzle, its swirl plates and orifice, the drop size distribution can be shifted towards larger drop diameters. Commercial nozzles of this type are available and have been used in simulators (Rawitz et al, 1972; Amerman et al, 1970; Grierson and Oades, 1977) but some workers have designed nozzles particularly for rainfall simulation, notably Hall (1969). More detailed descriptions of some selected nozzles of this type are contained in the Appendix.

Information on the calculation of optimum spacing of nozzle networks is available and uniformity of correctly designed systems is quite good. Suitable nozzles operated at the correct pressure have a drop size distribution similar to that of natural rainfalls. However the delivery rate is much higher than that of the equivalent rainfall, and therefore for accurate control of intensity some means of interrupting or intercepting the nozzle output is necessary. In a simulator with a large number of nozzles, the mechanics of this could be quite complex. It is not possible to reduce the intensity by lowering the supply pressure since this will change the atomisation characteristics and prevent proper drop formation.

An atomiser working on a completely different principle was also included in the early tests. The concentric twin fluid atomising nozzle has an inner fluid pipe into which the fluid is fed, and an outer pipe into which air is blown. Since the energy for atomisation comes from the air and not from the liquid pressure as in a conventional nozzle, the amount of liquid can be controlled independantly of the drop size.

This property overcomes one of the main problems of conventional nozzles, that the volume of liquid delivered is much too large. However, on testing the twin fluid nozzle it became apparent that the drop size spectrum was very narrow; a limited size range of drops was produced whose diameters decreased with increasing air pressure (see Appendix). Also, sprayed area was very small so that large numbers of nozzles would be required to cover a useful target area. The nozzle was therefore abandoned as it was felt that considerable work would be required to develop a nozzle system which preserved the good features of the type while having suitable drop size and uniformity.

Reducing the output of the nozzle array

In order to permit reproduction of the intensities of rain commonly encountered in Britain, the output of the nozzle network has to be attenuated in some way so that a range of intensities down to 0.5 mm per hour may be produced.

The operating pressure controls the actual rate of water emission from a swirl type nozzle but, since the pressure drop across the nozzle provides the energy for atomisation, it cannot be varied without altering the drop size distribution. Some workers (Bubenzer and Meyer) have tried rapid oscillation of the nozzle across a plot in order to reduce the apparent intensity. However, the ratio of reduction needed (down to 300:1) calls for considerable skill in engineering if the oscillation is to be sufficiently fast for there to be no noticeable intermittency in the resulting output.

As noted in the review section, a number of workers have tried rotating segment shutters to reduce the intensity of simulators. These devices provide an elegant solution to the problem for single nozzle simulators but, because one shutter assembly is required for each nozzle, the cost and complexity of equipping a multiple nozzle array is high.

An alternative solution which uses stationary shutters has been used by Salford University Department of Civil Engineering. These shutters work like a horizontal venetian blind and the amount of water allowed to pass through the shutter assembly is controlled by varying the angle of the shutter elements by means of a link rod connected to pegs on the ends of the shutters. A paper describing the construction of the unit in more detail is in preparation by the Department of Civil Engineering. The design of the shutter used in the Salford Simulator is satisfactory for the studies of runoff from soils for which the unit was designed, but has some shortcomings if used for pesticide work. The shutters produce drips which constitute a significant proportion of the simulator output at low intensities. These fall in lines upon the target area, imparting a marked systematic pattern to the output. Also control of intensity at levels below 5 mm/hour is difficult as a small shutter movement produces a large change in intensity. Various methods have been devised to overcome these problems and the detailed design, construction and performance of a rain simulator based on this method of construction will be described in a subsequent paper.

PRACTICAL CONSIDERATIONS

Structure

The height of the building to house the simulator should allow at least 5 m clear height below the drop forming elements if terminal velocity is important. Additional height assists when maintenance is necessary. Clear access to allow placement and removal of plants is also important to easy operation.

By their function, rainfall simulators make things wet, and all structures below the drop forming elements must be capable of withstanding repeated wetting without deterioration. All structural elements such as crossbeams and support wires are potential sources of drips and some means must be incorporated to prevent these drips entering the target area.

Another consequence of the conditions produced by a rain simulator is that walls, floor and electrical equipment must be suitable for use in wet conditions and that local electrical safety regulations must be satisfied.

Target area

Some simulators have a simple target area (often the floor of the laboratory). Other designs depend on moving either the source of drops, or the target, to increase uniformity as mentioned in the review section. If the target itself is to move, allowances must be made for the height of the target table when calculating fall distances.

A target area of a certain size needs a drop forming source capable of covering a larger area to maintain uniformity. For nozzle type simulators each point on the target typically receives most of its water from a "cell" of nine nozzles. To maintain this condition at the edges of the target, therefore, requires a source network extending at least one nozzle spacing beyond the target on all sides.

Control of air currents

Air currents within the building may interfere with the operation of the simulator. Design should preferably include provision for a door of some kind to separate the simulator from the rest of the building. A ribbon strip doorway, flexible strips which hang to form a curtain, is an alternative to a more conventional door but might be less convenient. The inner surface of the door must be resistant to splashing and high humidity.

Control of the environment

The humidity of the air contained within the simulator will rise to a high value when the simulator is operated. This is a desirable feature resembling the natural situation. The temperature could be controlled by mounting a heater/ cooler unit with thermostatic control inside the simulator and recirculating the air through it. Recirculation is more economical than treating incoming fresh air, and depletion of CO_2 or contamination problems are unlikely to occur. If air is conditioned, care must be taken to ensure that the air circulated does not markedly interfere with the pattern of rain deposition, while being adequate to maintain temperature within the room.

Light

The low levels of light normally associated with rainy conditions can be simulated if required by, for example, high pressure discharge lamps suitably protected and mounted. The mechanism of the simulator is likely to obscure lighting from above the drop forming elements so the lamps would have to be placed at the sides of the unit.

Water supply

The simulator must be capable of supplying the maximum total rainfall required. To do this it must either have a deioniser/filter/ feed capable of supplying the required rate of water indefinitely, or it must have a buffer tank which can be filled before the run, to supply the difference between the feed rate and application rate.

The size of buffer tank is given by: (outflow rate-inflow rate) x run time. Refill time (which is the minimum period between runs) is given by

$$\frac{(\text{Outflow rate} - \text{Inflow rate}) \times \text{run time}}{\text{Inflow rate}}$$

Obviously a large buffer tank will slow down operations by necessitating long refill times between runs, so a fast inflow and a small buffer tank is preferred. In nozzle type simulators where the excess rainfall is intercepted and returned to the tank by a drainage system, there may be a significant delay before water returns to the tank. The tank must be large enough to supply all the water needed during this period.

CONCLUSIONS

The design of rain simulation equipment is inevitably a compromise between specification, cost, complexity and ease of operation. The choice of priorities for the various factors lies with the experimenter, and the methods suggested in this paper are intended to assist this choice.

The criteria for a versatile simulator capable of operating at a wide range of intensities have been defined and have led to the conclusion that a network of swirl type nozzles offers the best approximation to a "natural" range of drop size distributions. The Salford nozzle had a drop size distribution like that of light rainfalls while the commercial swirl nozzles were a better approximation to heavier rains. Choice of a nozzle is further determined by other factors such as delivery volume and uniformity of delivery. The author tested nozzles which had already been described in the literature, or which were said to have suitable properties by their manufacturers. This approach which, it is appreciated, may have led to the inadvertent exclusion of equally suitable items, was adopted in order to reduce the work of initial evaluation down to a reasonable level. The reader is referred to the relevant authors for detailed accounts of ways of reducing intensity. Current work suggests that the slotted shutter offers the most promise for controlling intensity in multi-nozzle arrays.

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APPENDIX

CHARACTERISTICS OF SOME NOZZLES

Drop size distribution data are provided by the manufacturers for commercially made nozzles, and were obtained for the plastic nozzle made by Salford University by a modification of the method described by Hall (1970). Other tests were performed using the procedures described in detail later in this report under 'test methods'. Figure 1 shows the construction of some of the nozzles.

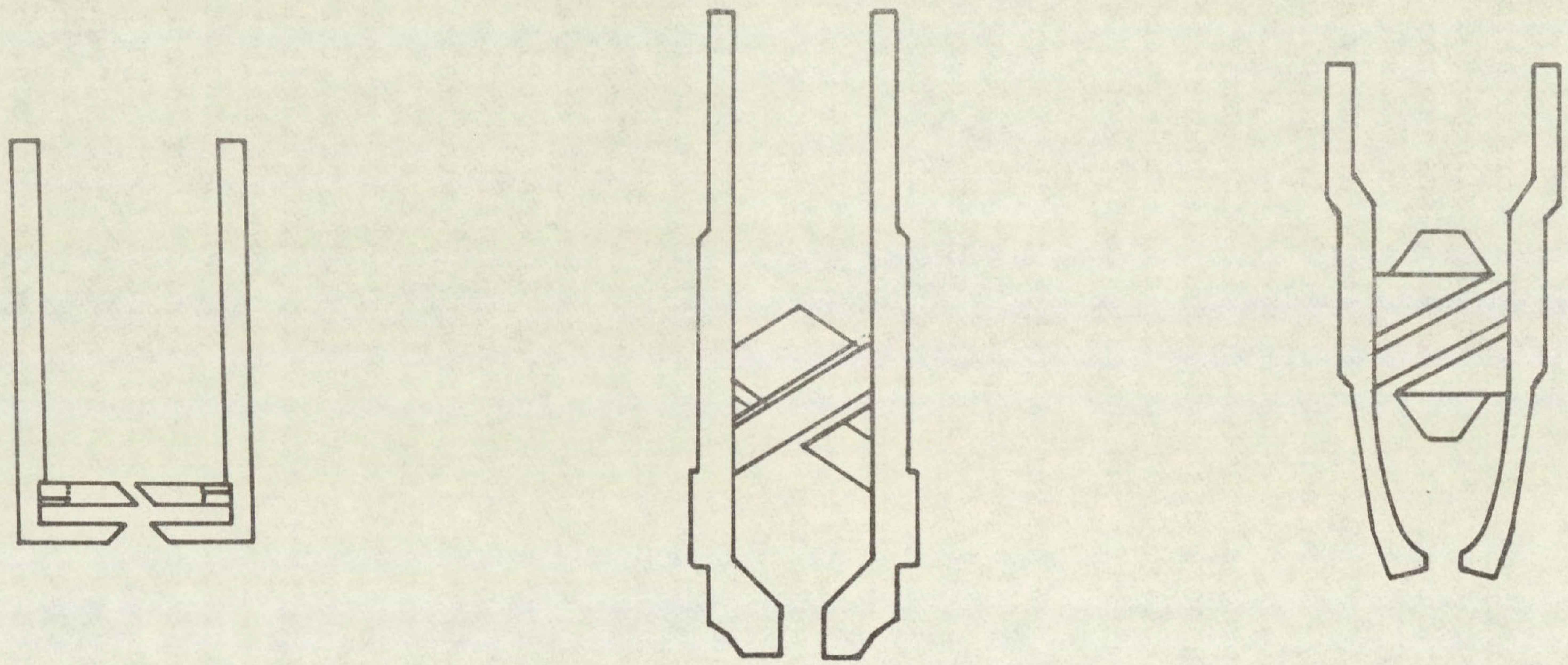
1. Imperial College Swirl Nozzle. This brass nozzle was developed by the Civil Engineering Department of Imperial College (Hall, 1969). The drop size distribution can be arranged, by choosing the correct operating pressure, to be similar to rainfalls in the range 0.5-3 mm/ hour. An example of the ratio between drop size distribution equivalent intensity and actual intensity is given by Hall (1970) where a nozzle set up to produce a distribution similar to that from a rainfall of 1.4 mm/hour in fact delivered 59 mm/hour, a 42:1 ratio. The nozzle produces a cone of liquid from which atomisation occurs; the impact pattern upon a distant target is therefore essentially a concentric one (Fig 2) and Hall (1969) has shown that such patterns can be overlapped to give good uniformity if the spacing is correctly chosen.

2. Salford Nozzle. A plastic version of the Imperial College nozzle has been developed (Jacob, 1978) which is more economical to make and has substantially the same characteristics as the original design. The construction of the nozzle is shown in Fig 1. It consists of a tube of PVC in which is inserted a flat swirl plate with four angled slots in it. Below the slotted plate is an orifice plate with a single central hole, countersunk on the outside. As the water passes through the swirl plate it acquires a circular motion which is retained as the water passes out of the orifice. The circular motion and the properties of the edge of the orifice control the atomisation. Readers are referred to Fraser (1957) for a detailed account of the mechanism of atomisation of this and other nozzles.

3. 80100 VeeJet (Spraying Systems). In rain simulation applications this nozzle is used at a low pressure: at 41 kPa (6 psi) its drop characteristics are similar to those of a 25 mm/hour rainfall, while progressively increasing the pressure shifts the drop spectrum in approximately the same way that the natural rainfall spectrum shifts with decreasing intensity. Because of its resemblance to natural rainfall drop spectra, the 80100 nozzle has been used in many simulators. However it shares with other nozzles the problem of delivering too high an intensity for the drop size distribution. Suitable overlapping arrays of this nozzle give fairly even distribution in one plane but because of the shape of the discharge from the nozzle, the array is rectangular in cell shape rather than square, and also varies in optimum dimensions according to the pressure. This makes it difficult to design an array which is uniform in two dimensions. Spraying Systems Corp. suggested the use of a type ¼G10 nozzle as the swirl type nozzle having the nearest drop size distribution to the 80100, but with a more convenient solid cone output.

4. Sprayco 5D. This is the nozzle used in the Purdue University sprinkling infiltrometer. It is claimed to give an even distribution (C_u 0.78 to 0.94 depending on intensity) over a circular area of 1.3 m^2. The nozzle is operated at 48 kPa, at which it delivers 70 mm/hour to the test area. Application rates have been reduced by using sector shutters beneath the nozzle - in this way a nearly continuous 'rain' of down to 2 mm/hour has been achieved. The drop size characteristics are similar to those of rainfall of about 8 mm/hour when

FIGURE 1 SECTIONAL DRAWINGS OF NOZZLES *(not to scale)*



Salford

Spraying Systems
$\frac{1}{4}$ GIO

Spraco
1131805

operated at 48 kPa. The current nearest equivalent from this company is the Sprayco 11381805 which has substantially similar characteristics.

5. Twin Fluid Atomiser. This nozzle uses a venturi formed from two concentric tubes. The inner tube is fed with water from a reservoir while the outer tube has air blown through it. The assembly thus resembles a paint sprayer nozzle, but is much larger, the outer pipe being some 30 mm in diameter, with an 8 mm orifice, and operates at lower air pressure in order to produce drops in the size range required. The particular nozzle tested was modified from a prototype produced by the National Institute of Agricultural Engineering. By operation at pressures in the range 0.35 to 1.4 kPa, drop formation can be controlled to lie in the range 0.3 to 1 mm diameter. Intensity can be separately controlled by varying the flow rate of liquid into the inner tube.

The unit was found to have a narrow range of drop sizes at any one air pressure, and to have very limited spatial distribution. At a distance of 4.1 m from the nozzle, 98% of the drops fell within a circle of 250 mm diameter.

TEST METHODS

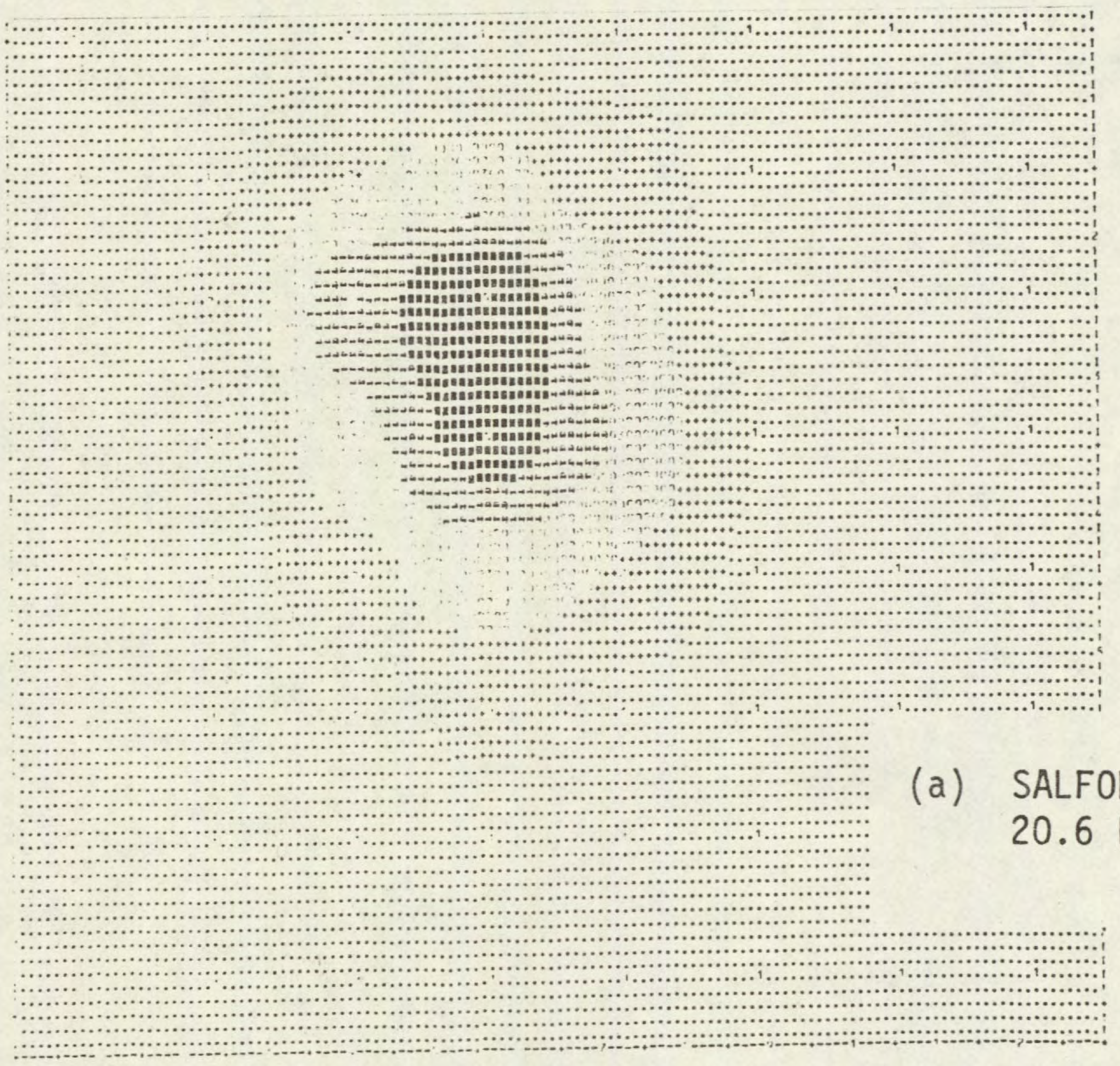
1. Drop size distributions. The drop spectrum at various pressures was determined by a modification of the stain method described by Hall (1970) and others. It was found that the method first adopted using Bromcresol blue which changes colour from yellow to blue on contact with water gave insufficient contrast to allow good resolution of small drops, so a solution of blue dye (acid turquoise in water) was pumped through the nozzle and the drops allowed to fall on to dry but otherwise untreated Whatman No. 1 filter paper. For all the tests the nozzle was mounted 4.1 m above the laboratory floor, which was marked with a grid of lines to locate measuring positions. Filter papers were exposed to the output of the nozzle in a box whose sliding lid had a slot cut in it. Exposures were made directly under the nozzle and also at 1 m radius as the drop spectrum changes with measuring position due to the varying trajectories of different drop sizes. The exposed papers were photographed using high contrast panchromatic film, and the sizes of the stain images measured and collected into size-groups using the Imanco Quantimet image analysing computer belonging to Rothamsted Experimental Station. (It is possible to scan the papers themselves by using a conventional television camera instead of the filmstrip camera attachment, but producing an intermediate negative allows closer control over illumination and contrast).

Graph 2 shows the weighted mean* drop size distributions for the three tested nozzles, at pressures which produced optimum performance.

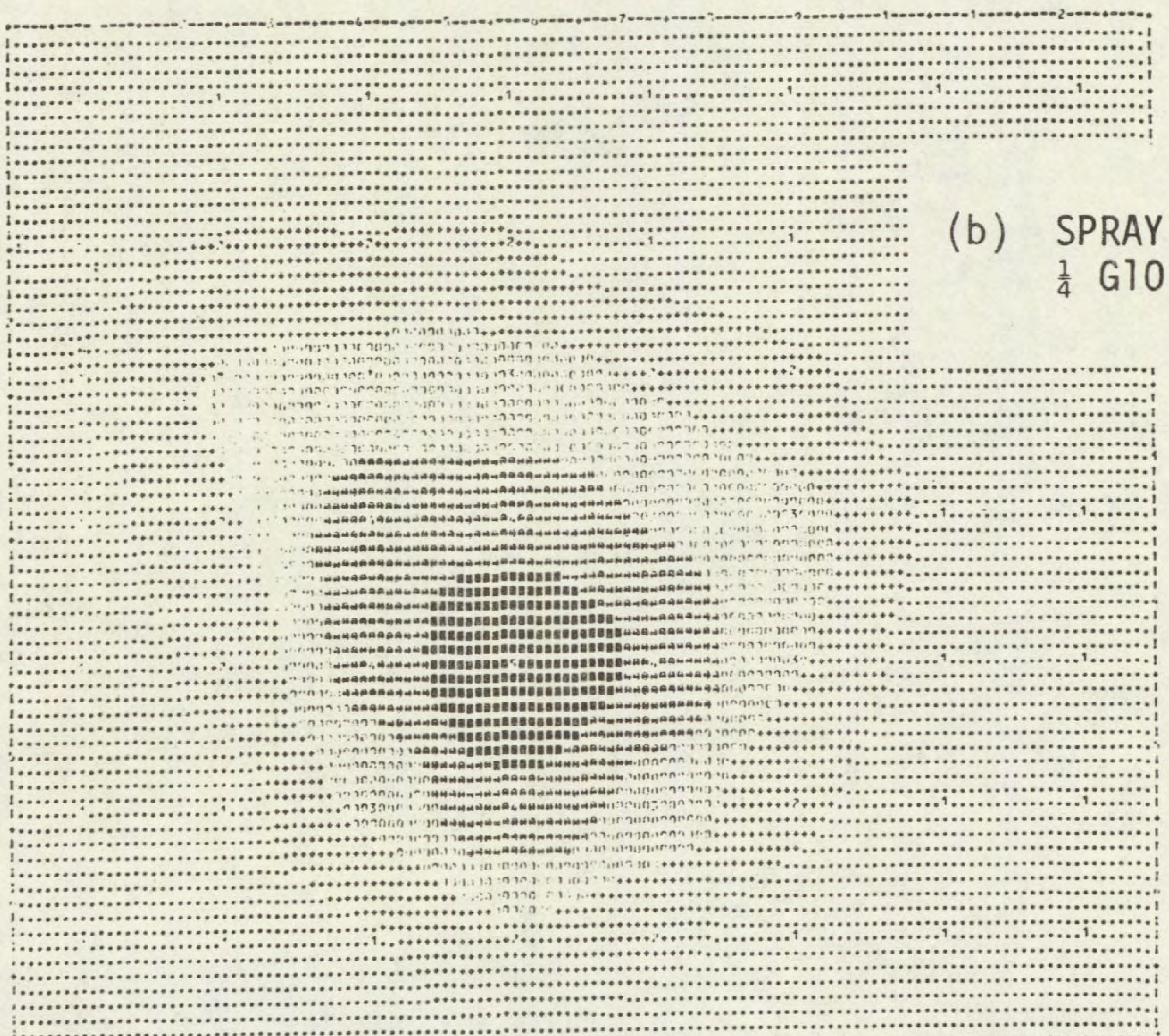
*Weighted mean values were calculated by dividing the nozzle output pattern into two concentric zones; the inner one, from the centre to 0.5 m radius, was considered to have the drop size characteristics of the 'centre' measurement, and the outer, from 0.5 m radius to the edge of the wetted area, considered to have the 'edge' distribution. The values obtained from these two sample positions were multiplied by the area of their respective zones, and added together.

Figure 2

Measured distributions of spray from nozzles



(a) SALFORD NOZZLE
20.6 kP

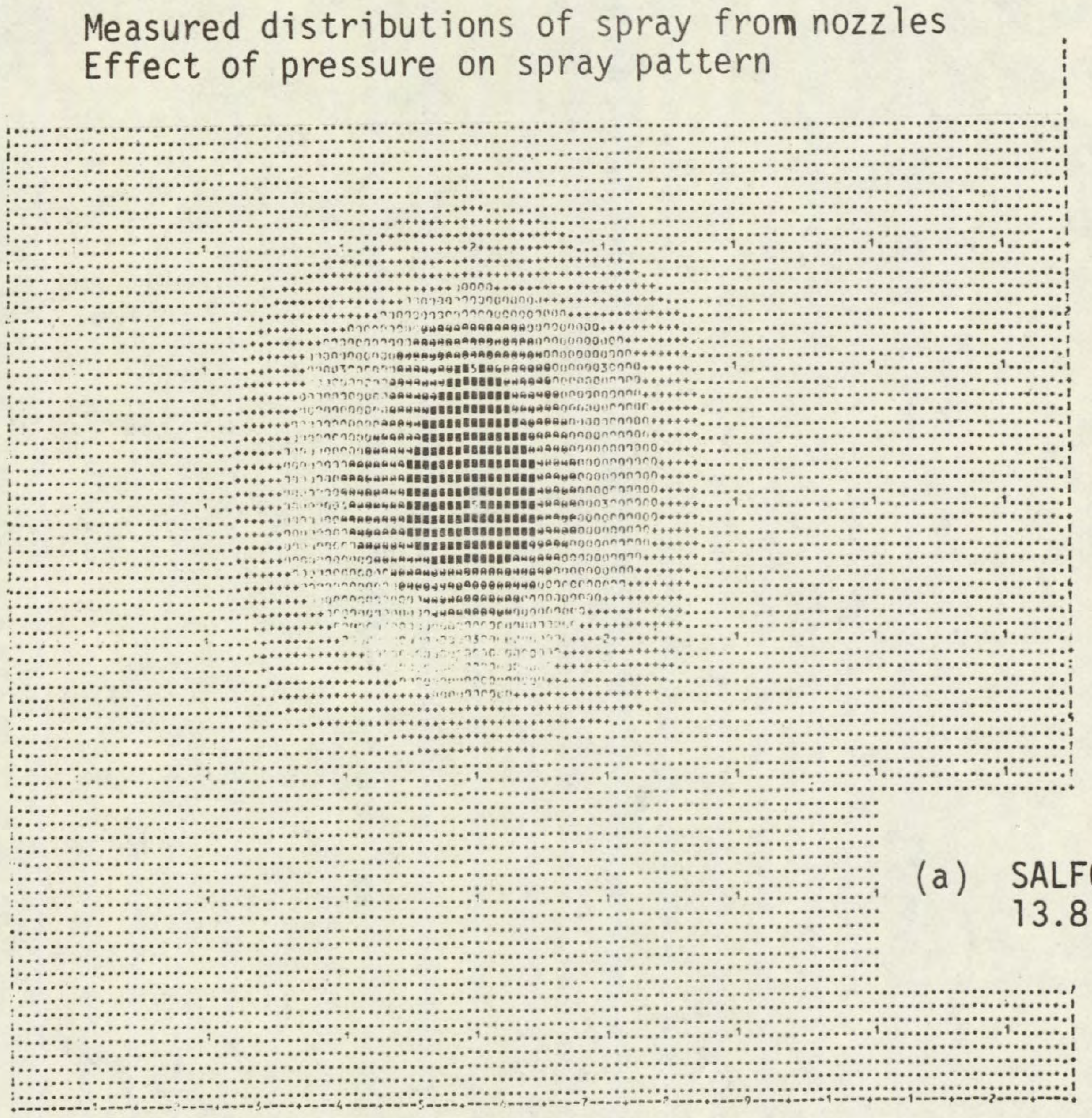


(b) SPRAYING SYSTEMS
$\frac{1}{4}$ G10 137 kPa

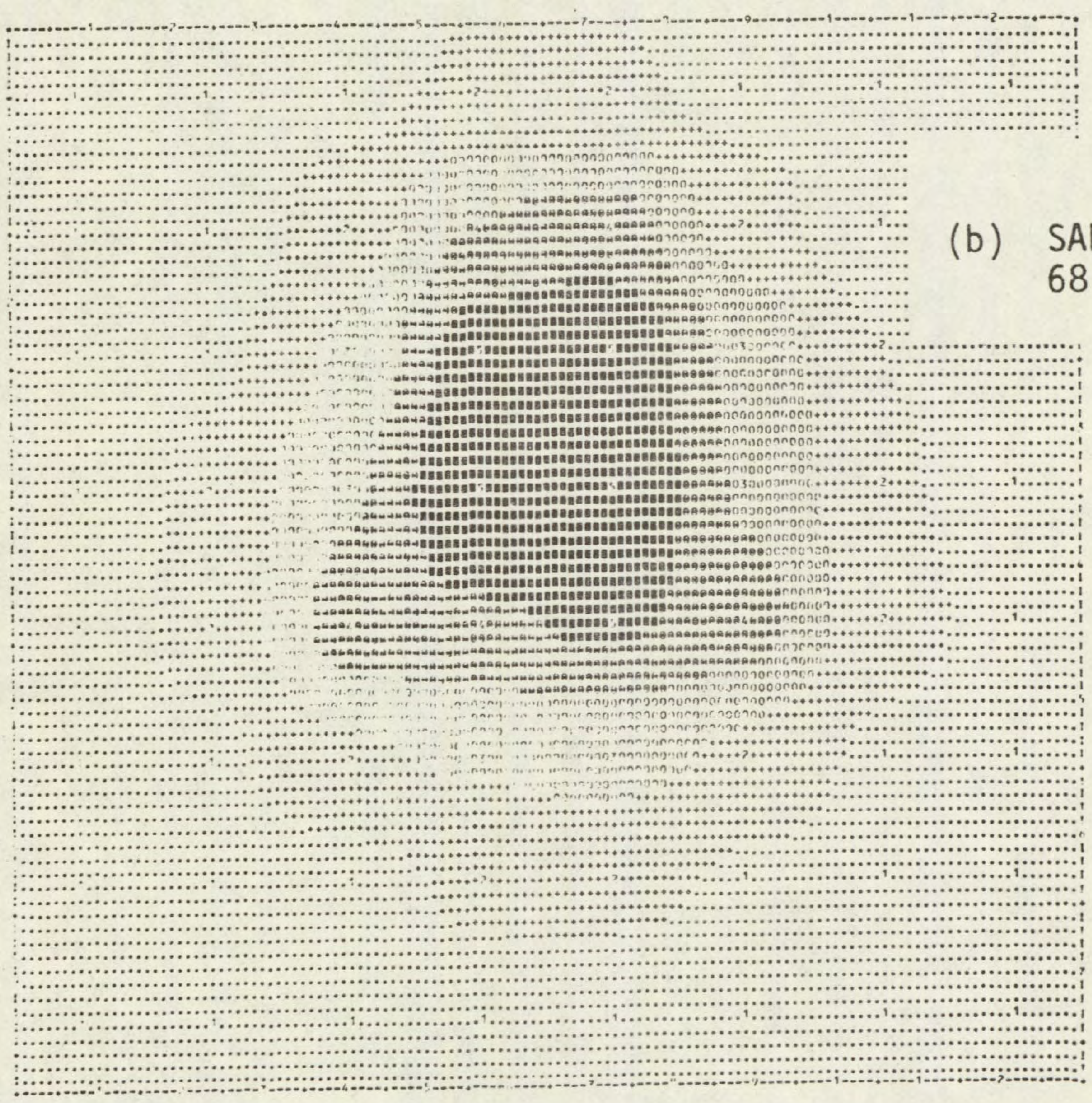
Each contour represents a band of 20% compared to the highest measurement

Figure 3

Measured distributions of spray from nozzles
Effect of pressure on spray pattern

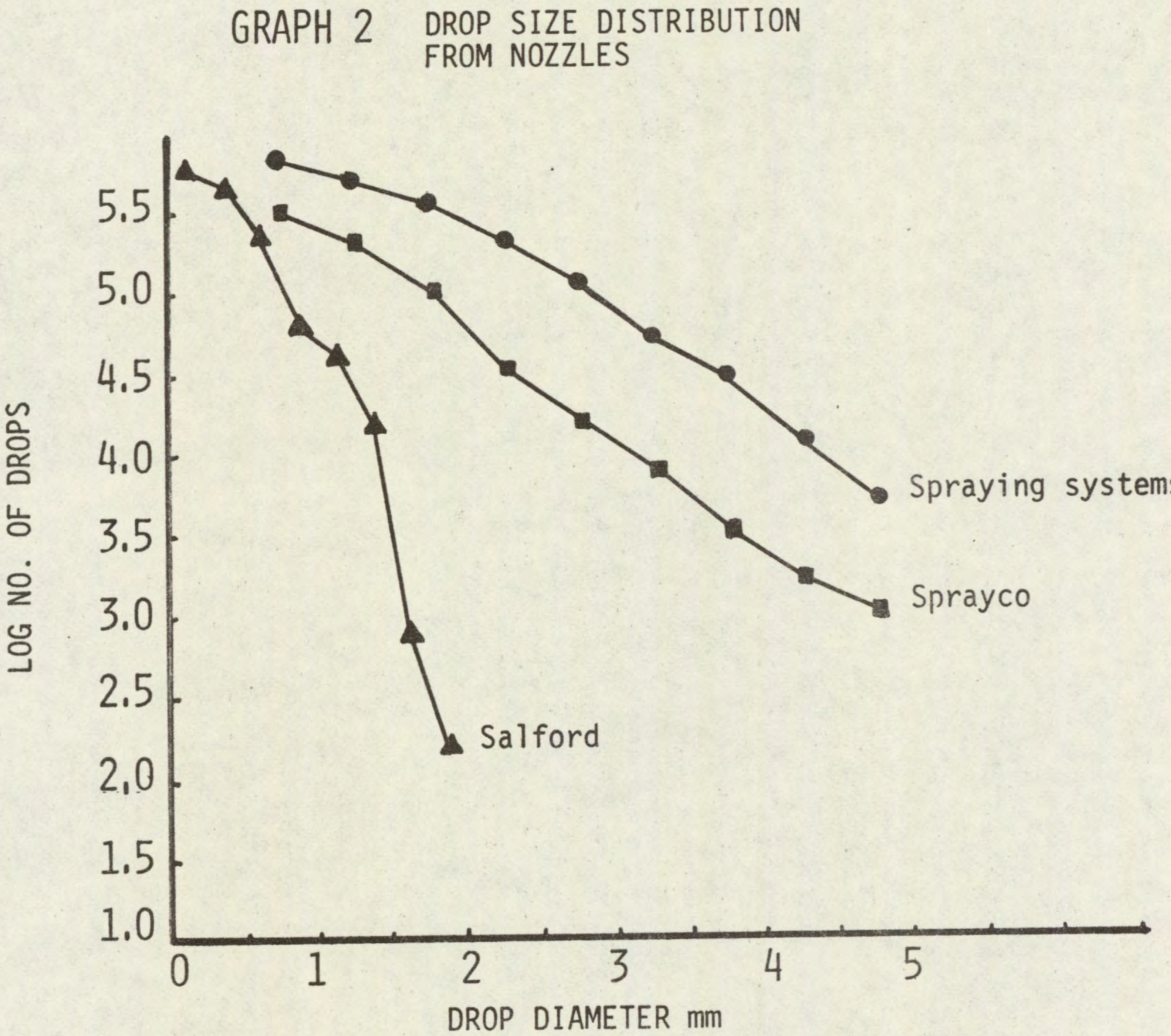


(a) SALFORD NOZZLE
13.8 kPa



(b) SALFORD NOZZLE
68 kPa

Each contour represents a band of 20% compared
to the highest measurement



<u>Output patterns</u>

Choice of a suitable nozzle for rain simulation is further influenced by the uniformity of the pattern formed by an array of similar nozzles spaced at regular intervals.

The optimum spacing for a given nozzle can be found by first measuring the output from a single nozzle by collecting the water in suitable containers arranged in a regular grid beneath the nozzle. The effect of nozzle spacing can then be predicted using a computer program to simulate the contribution of adjacent nozzles. The resulting pattern can be tested for uniformity using a suitable statistical test such as Christiansen's uniformity coefficient. To find out the optimum spacing for a grid of nozzles it is necessary to know the patterns of discharge produced by a single nozzle working at the pressures likely to be used. Using this information, it is possible to predict the patterns produced by various spacings of nozzle, and to calculate the probable uniformity of the resulting output.

The pattern was sampled using a grid of collecting tubes placed on the floor of the laboratory beneath the nozzle test rig. Initial testing was done with a grid spacing of 250 mm and more detailed tests with a spacing of 125 mm. Each tube is 50 mm high and 19 mm diameter. These tubes are tall enough to minimise splash errors, and can collect enough water to allow a test of 20-60 minutes duration, so short term variations have little effect.

The measured values were plotted using a mapping program to check that there were no marked asymmetries which might indicate a blocked or damaged nozzle, and the effect of overlapping the nozzle output patterns by various amounts was then calculated. Some specimen outputs from the mapping program are shown in Figs 2 and 3. Fig 2 shows mapped outputs from the Salford and Spraying Systems nozzles at 21 and 138 kPA respectively. Fig 3 shows the change in pattern caused in the Salford nozzle by an increase in pressure from 13.8 to 68 kPa. The output from the calculation is in the form of a grid of numbers corresponding to the input measurements, but with values which would be obtained from an array of nozzles equally spaced at the chosen distances. The calculation was executed several times with different spacings and the sets of outputs so obtained were tested for uniformity.

Uniformity was assessed by calculating Christiansen's uniformity coefficient, a widely used measure of the uniformity of distribution of irrigation and sprayer outputs.

Table 5.

Calculated Uniformity Coefficients for Simulated Nozzle Arrays

Pressure		Array Spacing (mm)									
PSI	kPa	125	250	375	500	750	1000	1250	1500	1750	
2	13.8		0.98		0.98	0.88	0.88				Salford
4	27.6		0.96		0.98	0.95	0.87				Nozzle
10	69		0.98		0.98	0.96	0.87				
10	68		0.98		0.98	0.89	0.86	0.72	0.75	0.81	Sprayco 115805
12.5	86		0.96		0.96	0.83	0.86	0.68	0.73	0.79	
15	103		0.96		0.96	0.83	0.87	0.68	0.67	0.79	
10	69		0.93		0.93	0.80	0.68	0.54			Spraying
15	103		0.98		0.98	0.93	0.85	0.67			Systems
20	138		0.98		0.98	0.94	0.90	0.74			¼ GIO
0.5	3.5	0.65	0.22	0.11							Twin Fluid Atomiser

Table 6.

Pressure		Approximate delivery rate (mm/hr)		
PSI	kPa	Salford	Sprayco	Spraying Systems
2	13.8	88		
3	20.7	105		
4	27.6	117		
5	34.5	128		
10	69	170	620	490
12.5	86		700	550
15	103		860	600
20	138			700

Where each measurement represents a sample area of equal size (i.e. an equally spaced grid of measurements) the estimation of C_u is performed by the equation $Cu = 1 - \frac{|x - \bar{x}|}{}$ where x_1 ..... x_n are the individual observations, and $\bar{x}$ is the mean of the observations. Cu tends to 1 for uniform distribution.

From Table 5 the following points are noticeable:

1. The twin fluid atomiser produces a pattern which is very difficult to overlap effectively. Because of this, and the restricted range of drop sizes available at any given air pressure, further tests on this nozzle were not carried out.

2. The Spraying Systems, Sprayco and Salford nozzles all had acceptable uniformities at spacings of 500mm. Uniformity then decreased with increased spacing although the Sprayco nozzle had a second peak of uniformity at a spacing of 1750mm.

Table 6 shows the approximate amounts of 'rain' delivered by the nozzles for optimum spacing and at normal operating pressures, based on the calculated values for the overlapped outputs.

From this table it appears that the Salford nozzle delivers less liquid than the other nozzles, when operated at pressures which produce the most suitable drop size distributions. Since all nozzles produce a volume of water much in excess of that required, the nozzle which produces the lowest volume is to be preferred.

Summary of Test Results

1. Drop size distribution. The three swirl type nozzles tested all had drop spectra which approximated to real rain. The two commercial nozzles had similar drop spectra, resembling the distributions recorded in rain of intensities greater than 20 mm/hour; the Salford unit had a drop spectrum which was more nearly like that of very low rainfall though it lacks the ability to produce drops larger than 3mm diameter, even when operated at the lowest pressure for satisfactory atomization.

All the nozzles 'sorted' the drops to some extent, throwing more large drops to the edge of the pattern. This effect can be masked by spacing the nozzles close enough so that each point on the target receives drops from a number of nozzles.

2. Output patterns. The three nozzles produced patterns approximately conical in cross section which could be overlapped effectively only at close spacings.

Although the patterns changed with pressure, the uniformity coefficient for both the Sprayco and Salford nozzles remained high over the working range when tested at the fixed spacing of 500mm. The pattern of the twin fluid atomizer was difficult to overlap effectively even at close spacings.

3. Discharge rate. Due to its slightly different construction, the Salford nozzles required less pressure, and emitted less water, than the other nozzles when producing a similar spectrum of drop sizes.

On the basis of this evaluation, and because of its low cost of manufacture, including the ability to chemically weld it to PVC supply pipes, the Salford nozzle was chosen as the most suitable for a laboratory rainfall simulator meeting the design demands laid down earlier.

ABBREVIATIONS

ångström	Å	freezing point	f.p.
Abstract	Abs.	from summary	F.s.
acid equivalent*	a.e.	gallon	gal
acre	ac	gallons per hour	gal/h
active ingredient*	a.i.	gallons per acre	gal/ac
approximately equal to*	≃	gas liquid chromatography	GLC
aqueous concentrate	a.c.	gramme	g
bibliography	bibl.	hectare	ha
boiling point	b.p.	hectokilogram	hkg
bushel	bu	high volume	HV
centigrade	C	horse power	hp
centimetre*	cm	hour	h
concentrated	concd	hundredweight*	cwt
concentration	concn	hydrogen ion concentration*	pH
concentration x time product	ct	inch	in.
concentration required to kill 50% test animals	LC50	infra red	i.r.
		kilogramme	kg
cubic centimetre*	cm^3	kilo ($x10^3$)	k
cubic foot*	ft^3	less than	<
cubic inch*	in^3	litre	l.
cubic metre*	m^3	low volume	LV
cubic yard*	yd^3	maximum	max.
cultivar(s)	cv.	median lethal dose	LD50
curie*	Ci	medium volume	MV
degree Celsius*	^oC	melting point	m.p.
degree centigrade	^oC	metre	m
degree Fahrenheit*	^oF	micro ($x10^{-6}$)	µ
diameter	diam.	microgramme*	µg
diameter at breast height	d.b.h.	micromicro (pico: $x10^{-12}$)*	µµ
divided by*	÷ or /	micrometre (micron)*	µm (or µ)
dry matter	d.m.	micron (micrometre)*†	µm (or µ)
emulsifiable concentrate	e.c.	miles per hour*	mile/h
		milli ($x10^{-3}$)	m
equal to*	=	milliequivalent*	m.equiv.
fluid	fl.	milligramme	mg
foot	ft	millilitre	ml

† The name micrometre is preferred to micron and µm is preferred to µ.

millimetre*	mm
millimicro* (nano: x10^{-9})	n or mµ
minimum	min.
minus	-
minute	min
molar concentration*	M (small cap)
molecule, molecular	mol.
more than	>
multiplied by*	x
normal concentration*	N (small cap)
not dated	n.d.
oil miscible concentrate	o.m.c. (tables only)
organic matter	o.m.
ounce	oz
ounces per gallon	oz/gal
page	p.
pages	pp.
parts per million	ppm
parts per million by volume	ppmv
parts per million by weight	ppmw
percent(age)	%
pico (micromicro: x10^{-12})	p or µµ
pint	pint
pints per acre	pints/ac
plus or minus*	$\pm$
post-emergence	post-em
pound	lb
pound per acre*	lb/ac
pounds per minute	lb/min
pound per square inch*	lb/in^2
powder for dry application	p. (tables only)
power take off	p.t.o.
precipitate (noun)	ppt.
pre-emergence	pre-em.
quart	quart
relative humidity	r.h.
revolution per minute*	rev/min
second	s
soluble concentrate	s.c.
soluble powder	s.p.
solution	soln
species (singular)	sp.
species (plural)	spp.
specific gravity	sp. gr.
square foot*	ft^2
square inch	in^2
square metre*	m^2
square root of*	$\sqrt{\ }$
sub-species*	ssp.
summary	s.
temperature	temp.
ton	ton
tonne	t
ultra-low volume	ULV
ultra violet	u.v.
vapour density	v.d.
vapour pressure	v.p.
<u>varietas</u>	var.
volt	V
volume	vol.
volume per volume	v/v
water soluble powder	w.s.p. (tables only)
watt	W
weight	wt
weight per volume*	w/v
weight per weight*	w/w
wettable powder	w.p.
yard	yd
yards per minute	yd/min

* Those marked * should normally be used in the text as well as in tables etc.

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